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ONR LONDON CONFERENCE REPORT

C-6-77

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FIFTH INTERNATIONAL SYMPOSIUM ON MILITARY APPLICATIONS OF BLAST SIMULATION

W. G. SOPER

22 JUNE 1977

UNITED STATES OF AMERICA

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ONRL — C-6-77	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ~~FIFTH~~ INTERNATIONAL SYMPOSIUM ON MILITARY APPLICATIONS OF BLAST SIMULATION (5th).		5. TYPE OF REPORT & PERIOD COVERED Conference rept. 6. PERFORMING ORG. REPORT NUMBER C-6-77
7. AUTHOR(s) W. G./SOPER		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Office of Naval Research, Branch Office, London, Box 39, FPO New York 09510		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS 12 10p.		12. REPORT DATE 11 22 June 1977 13. NUMBER OF PAGES 8
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

blast, simulation, scaling, shock waves

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A review is given of papers presented at the subject Symposium, which was held in Stockholm, Sweden, 23-26 May 1977. Principa emphasis in the review is placed on advances in shock tube design, new instrumentation, and the use of scale models in blast research.

Several short shock-tubes driven by sources in parallel are described, and the success of cube-root scaling of magazine explosions and blast cratering is discussed.

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S/N 0102-014-6601

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FIFTH INTERNATIONAL SYMPOSIUM ON MILITARY APPLICATIONS OF BLAST SIMULATION

INTRODUCTION

Held in Stockholm on 23-26 May, this was the fifth gathering of an international group that meets at two- to three-year intervals to discuss techniques for simulating blast effects of large (primarily nuclear) charges. The tone was nicely set in the opening address by the Swedish Minister of Defense, who expressed his appreciation to the group for its contribution in determining by "peaceful means" the consequences of the "most disastrous events." He believes that this has had a significant deterrent effect regarding nuclear war, and he expressed the wish that such simulation might be available in other areas of technology--or even human relations--so that the outcome of untried courses of action might be ascertained in advance, without risk.

Approximately 50 papers were presented in seven sessions that treated the following topics: blast simulators, shock waves in non-gaseous media, OPERATION DICE THROW (a 628-ton ammonium nitrate blast trial), target response, modeling and scaling, blast phenomenology, and soil liquefaction. This report will attempt to cover the more novel work and that which may have application outside the specific area addressed in the Symposium. Omitted from discussion will be the numerous papers on blast damage to various targets (aircraft, vehicles, shelters, etc.) in full-scale field trials.

BLAST SIMULATORS

This session dealt primarily with the use of shock tubes to simulate the pressure-time profile of nuclear blast. In an effort to reduce construction and maintenance costs, researchers are tending away from the ideal simulator--the slender, conical tube that represents a small sector of a spherical explosion. Instead, much shorter structures are being studied, usually with stepwise changes in cross-sectional area, and with energy sources grouped in parallel over the breech end to obtain a flat shock front.

H. O. Amann (Ernst Mach Institut, FRG) described experiments with three compressed-air-driven shock-tube sources mounted along one diameter of the breech cross section of a larger tube. Planar shocks, acceptably free from transverse disturbances, are obtained in the larger tube only if the three sources are fired with high simultaneity. For his setup, where the main tube diameter is 10.5 cm, the maximum tolerable spread in firing times

is about 5 μsec. This is achieved by breaking diaphragm seals with exploding bridgewires connected in series to a large capacitor.

A group from the Centre d'Etudes de Gramat, Gramat, France, described their work in designing a blast simulator with a test section of 12-m width and 7-m height. Now under construction, the facility will employ seven shock tubes of circular cross section driving a larger tube of semi-circular cross section. The source tubes will be powered by compressed air or by combustion of a H_2-O_2 mixture. A novel feature will be an "active" reflection eliminator at the muzzle. An arrangement of steel flaps resembling a Venetian blind, this device will be operated during each shot to vary the muzzle impedance and preclude reflections. The flaps will be driven hydraulically according to a program developed empirically for each shock strength. Some skepticism was expressed by the audience regarding the workability of the idea, but the need is clear; rarefactions return quickly from the muzzle of a short tube to alter the wave profile at the test section.

The Sandia Corporation of Albuquerque has recently been experimenting with a shock tube in which a 6-m-dia. main section is driven by a single smaller tube loaded with Primacord explosive (PETN). This work was begun after the DASACON conical blast simulator at NSWC, Dahlgren, was shut down in 1974. M. G. Vigil, who presented a status report, stated that "noisy" shock profiles and short pulse durations are current problems. Backward detonation of the Primacord (i.e., from muzzle end to breech end of charge) has been found to increase pulse duration by 20%. In an effort to improve performance further, the 61-m length of the driver tube is now being increased.

Recent work in the large simulator at the Atomic Weapons Research Establishment, Foulness, England, was described by P. M. Clare. While there was some discussion of the helical Primacord source that Foulness has pioneered, most of the presentation dealt with the use of aqueous foams to improve shock profile. It has been found that filling sections of the tube near the explosive source with low-cost, detergent/water foams reduces noise in the pressure trace and alters the basic profile to match more closely the pulse from a spherical charge in free air. The foam is produced by standard firefighting equipment.

The session closed with a presentation of perhaps the ultimate in short blast simulators--a vented box in which the test item and the explosive charge are placed, separated by a foam plastic buffer. Developed at the Southwest Research Institute in San

Antonio, the device is intended to simulate only short-duration blast pulses from small missile warheads. Judicious adjustment of vent area and buffer thickness produces pulses of acceptable shape and smoothness. An additional feature of the facility is that fragments can be fired into the test object during the blast test.

SHOCK WAVES IN NON-GASEOUS MEDIA

The most basic physical investigation reported was that by P. Chartagnac (Centre d'Etudes de Gramat, Gramat, France) on the dynamic behavior of limestone. Through a series of high-pressure experiments of the type developed in the recent past for studying metals, equation-of-state data were determined for limestone to pressures of 650 kbar. The elastic limit was found to be 6.2 kbar and the hydrodynamic limit (the pressure at which material strength ceases to have significant effect on the stress field) 260 kbar. Fracture and compaction of the crystal lattice occur above 100 kbar, with the consequence that the material does not recover its original volume upon load removal. However, the residual volume passes through a minimum at about 300 kbar. For higher pressures, the crushed material actually recovers more fully. (Such anomalous behavior of porous materials has been discussed by Zel'dovich and Raizer, *Physics of Shock Waves and High Temperature Hydrodynamic Phenomena*, Vol. 2.) The work also determined the deviatoric stress (a measure of the material's resistance to plastic flow) in the region between the elastic and the hydrodynamic limits. The result shows that the von Mises yield condition, widely used in elastic-plastic flow computations, is a poor approximation for limestone.

The remarkable shock-damping properties of aqueous foams were discussed in a paper by J. de Krasinski (University of Calgary, Canada). A highly instrumented, vertical, shock tube was used to determine the alteration in pulse profile as a shock passes along a column of foam. Several types of foam were investigated, each with a range of void fraction (VF) (volume of air/total volume of foam) from 0.5 to about 0.9.

Foam produces a drastic reduction in shock velocity, evidently because it increases the density of the medium without appreciable change in the compressibility. A typical shock velocity for VF = 0.6 is 80 ft/sec, while that in free air is over 1,000 ft/sec! Marked attenuation of the shock also occurs. Krasinski's data show that a triangular pulse of 5-msec duration is reduced to half its initial intensity after traveling about 0.5 m. Most of his work has dealt with foams of very small bubble size (0.003 to 0.004 in.) produced from commercial shaving preparations. The life of these foams is about 48 hours. The detergent-based

foams discussed by P. M. Clare, on the other hand, have bubble sizes of about 0.5 in. and much shorter lives. After Krasinski's paper, in fact, there was a spirited discussion of the relative merits of Palmolive Rapid Shave and Expandal household detergent!

There was also a discussion of the mechanism by which foam attenuates shock pressure. Some contributors believed that the energy is converted into kinetic energy of the liquid in the foam, and is accordingly still available for producing damage to a test object. Others maintained that the energy is degraded directly to heat, and is effectively lost. The surprising fact is that no one has measured the dynamic, or stagnation, pressure behind a shock wave in foam. Such a measurement would reveal the contribution of the kinetic energy of particle motion and would resolve this question.

T. F. Kennedy (Defense Nuclear Agency, Washington, D.C.) reviewed current instrumentation for monitoring shock waves in soil. Largely through development sponsored by DNA, there are now transducers that can be buried at the blast test site to determine stress, acceleration, and particle velocity in the soil as functions of time. Such data will permit the development of accurate equations of state for various soils. Further, these instruments are contributing to the understanding of earth movement during explosive cratering, an area that is at present poorly understood.

SCALE MODEL STUDIES

Because of the expense and environmental impact of full-scale explosive trials, much of the experimental blast work conducted today utilizes small-scale models. The most striking demonstration of the power of the model approach was presented by G. A. Coulter (U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD), in a comparative study of explosions in full-scale munition storage magazines and in 1/50-scale geometric models. In the single full-scale test, an earth-covered magazine was destroyed by detonation of 100,000 lb of stored explosive. The model magazines were constructed by covering a thin metal shell with a special soil, a fine sand mixed with oil to improve cohesiveness. Charge weight in the model was 0.8 lb, or $100{,}000 \div (50)^3$. Since the objective was to investigate the validity of the model in regard to pressures generated about the site of the magazine, pressure-time data were acquired at a network of points at both the full-scale and the model sites.

It should be noted that the validity of such modeling is suspect because the effects of gravity are ignored. Strict scaling would require constancy of the product $G\ell$ between the full-scale and model systems, where G denotes the acceleration of gravity and

ℓ a characteristic length of the system. Rigorously, then, a 1/50-scale model should be operated in a gravitational field of 50 g.

In spite of this defect, Coulter's models gave excellent results. Peak pressure data for the large and small systems fall nicely onto a single curve when plotted against scaled distance. One must conclude that, during the time when the important features of the blast field are developing, the effect of gravity on the behavior of the magazine is negligible. (It is well known that the behavior in later times, as reflected in the debris pattern, does not follow the scaling law.) Coulter concluded that such geometrically scaled models give reliable data for pressure fields, and that they can be used to establish safe separation distances for magazines. The paper also included model data for full-scale charge weights up to 500,000 lb and for several thicknesses of earth cover on the bunker.

A similar series of model experiments, but in 1/10 scale, were reported by H. A. Metz of Basler and Hofmann AG, Zurich. In the writer's opinion, however, the work is of limited value because the data are presented incorrectly. Metz varied charge weight W over a sizable range--0.05 kg to 50 kg--while holding the dimensions of the model magazine fixed. He then attempted to show that peak pressure is a function only of the scaled distance $R/W^{1/3}$, where R is the distance from the magazine. This was found not to be the case, and he concluded that geometric or "cube-root" scaling is not valid.

There is, in fact, no basis in modeling theory for his expectation. The theory states that peak pressure will be a function of $R/W^{1/3}$, but only among geometrically similar systems such as Coulter's full-scale magazine with 100,000 lb of explosive and his 1/50-scale model with 0.8 lb. The systems that Metz tested were not geometrically similar, as magazine size was fixed while explosive mass was varied. Thus, no conclusion regarding the validity of the model can be drawn. Of course, by taking advantage of Coulter's proof of model validity, Metz's results can be scaled up to large magazines. In doing so, the data for a given model must be applied only to a larger system that is geometrically similar; i.e., one that has the same ratio of charge weight to magazine volume (or charge length to magazine length).

Further confirmation of geometric models was presented by A. Jenssen (Norwegian Defense Construction Service, Oslo) in a comparative study of the blast field outside the entrance tunnel of an ammunition storage chamber situated in solid rock. Peak-pressure isobars were compared for tests on full-scale and 1/100-scale systems, with satisfactory results. Inasmuch as no

significant structural deformation occurs in this case, gravitational effects are negligible, and validity of the modeling would be expected.

A proposed safety device for sealing such entrance tunnels in event of internal blast was investigated in small scale by the Ernst Mach Institute. Placed in the tunnel is a massive sliding block--essentially a piston--that can move toward the entrance and seat against a shoulder in the wall, sealing the tunnel. In its normal open position, the block is bypassed by a walkway that is sealed off after the block has moved about one tunnel diameter. Model tests in 1/50 scale showed that detonation of less than 50,000 kg of TNT in the full-scale tunnel would not close the "valve" before some of the blast had escaped through the bypass. Larger charges, though, moved the block rapidly into the closed position and sealed the tunnel before the shock wave could travel around the bypass. This suppression of high-yield blasts would permit a substantial reduction in the hazard zone about the storage site.

A situation where gravity plays a dominant role in system behavior, and where cube-root scaling fails, was described by F. M. Sauer (Physics International, San Leandro, CA) in his discussion of earth motion during cratering. With test data (obtained via transducers developed by DNA) for charges of 256 lb to 102 tons in weight, he showed that particle velocity in the soil does not obey the cube-root scaling law. For example, the time at which maximum crater diameter is reached is found to vary as $W^{1/6}$ rather than as $W^{1/3}$. Sauer referred to some computational models that indicate that the exponent should vary from 1/3 for small systems, where soil strength is the controlling factor, to 1/7 for very large systems, where gravitational forces dominate.

The writer, in seeking some understanding of the behavior of very large systems, has considered the situation of blast above the surface of an inviscid liquid, a substance of zero strength. Dimensional analysis quickly reveals that the time to maximum crater diameter is proportional to $W^{1/8}$, while the maximum diameter itself is proportional to $W^{1/4}$ (vs $W^{1/3}$ in cube-root scaling). Thus it appears that the timing of events in earth motion from blast is more sensitive to gravitational effects than are the displacements produced by the blast. This is consistent with the fact that cube-root scaling has been moderately successful in predicting crater dimensions, despite Sauer's discoveries regarding the time scale.

While not scale model work, progress at BRL, Aberdeen, in developing an improved criterion for target damage will be mentioned here. The susceptibility of military targets to blast has

traditionally been expressed in terms of "P-I curves," P denoting peak pressure in the incident blast wave and I its area, or impulse. For a pulse of a given shape (triangular, rectangular, exponential, etc.), these two parameters completely characterize the loading and, therefore, the target response, or damage. Real blast pulses, however, are never "clean," and peak pressure becomes an unreliable parameter for characterizing the load. The BRL work, as reported by R. N. Schumacher, has shown that a better parameter is the first moment, M_1, of the pressure-time distribution. Schumacher finds that damage data for a given target under different forms of loading cluster more closely to a single curve in M_1-I coordinates than in P-I coordinates.

SOIL LIQUEFACTION

This session dealt with the phenomenon in which certain (usually sandy) soils of high water content lose their resistance to shear stress following an impact or earth shock. This "liquefaction" has been responsible for catastrophic settling of buildings during earthquakes. The basic mechanism appears to arise from the fact that sands are not normally in their most compact, or minimum-volume, state. Sufficient shock can then produce a rearrangement of soil particles that shrinks the volume of the solid aggregate. If the water content is sufficiently high in this instance, any structure resting upon the soil is left suspended by water pressure alone, and settling ensues.

Both experimental and analytical approaches to the study of soil liquefaction were presented at the Symposium. J. Studer (Swiss Federal Institute of Technology, Zurich) reported experiments in which a volume of saturated sand was subjected to pressure pulses in a shock tube. Distributed through the soil were two types of piezoelectric pressure transducers. One type, mounted within a porous shell that carried the pressure of the sand grains, sensed only the pore-water pressure. The other type was insensitive to water pressure and responded only to the intergranular pressure. With this instrumentation, the variation of pore-water and intergranular pressures during the shock loading was monitored. Complete loss of intergranular pressure (the condition of liquefaction) was observed for sands of low and medium density.

E. G. Prater of the same institute described a mathematical model for soil liquefaction. The starting point is Biot's theory for the properties of a fluid-saturated granular substance. The water is treated as a linear elastic medium, while the soil is assumed to have elastic-plastic properties. Numerical solution of the governing differential equations, for blast loads applied to the soil surface, reveals a transfer of supportive stress from solid to fluid that is encouragingly similar to the shock tube results.

Some underground trials of small charges (3 kg) were described by R. W. Trense (Technological Laboratory, TNO, Rijswijk, The Netherlands). Transducers to measure total pressure (water + intergranular) in three orthogonal directions were buried at charge depth (11 m) at a radial distance of 6.5 m. Peak pressures of about 100 bar were recorded, and shear stresses as high as 20 bar were deduced from the differences in pressure. Without separate indication of the water and grain pressures, however, firm conclusions regarding liquefaction are difficult to draw.

There is a striking similarity between the phenomena involved in soil liquefaction and those accompanying the passage of propellant gases through a bed of gun propellant (see Soper, *Combustion and Flame* 20, pp. 157-162 (1973), 22, pp. 273-276 (1974), and 24, pp. 199-202 (1975). Early in the ignition process, grain pressure plays an important role in imparting motion to the propellant ahead of the advancing flame front. Behind the flame front, the gas pressure in the "pores," or intergranular spaces, rapidly builds up, while intergranular pressure diminishes. These remarks are made only to illustrate that the analytical models and the instrumentation being developed for soil liquefaction studies have direct application to present tri-service efforts to develop better models for ignition and interior ballistics of gun propellant.

PROCEEDINGS

The proceedings of this Symposium have been published in two volumes. A limited number of copies are available from: Royal Swedish Fortifications Administration, S-104, 50 Stockholm, Sweden (price unknown).